In situ Resource Utilization for Processing of Metal Alloys on Lunar and Mars Bases

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Abstract

Current plans for practical missions leading to a sustained human presence on our Moon and Mars rely on utilizing their *in situ* resources. Initially, resource availability must be assessed followed by the development of economically acceptable and technically feasible extractive processes. In regard to metals processing and fabrication, the lower gravity level on the Moon (0.125 g) and Mars (0.369 g) will dramatically change the presently accepted hierarchy of materials in terms of specific properties, a factor which must be understood and exploited. Furthermore, significant changes are expected in the behavior of liquid metals during processing. In metal casting, for example, mold filling and associated solidification processes have to be reevaluated. Finally, microstructural development and therefore material properties, presently being documented through on-going research in microgravity science and applications, need to be understood and scaled to the reduced gravity environments. These and other issues are addressed in this paper.

Introduction

Interest in the materials processing in reduced gravity began in the late 1960's with planning for the Skylab orbital space station. Early experiments focused on welding, brazing, and solidification processes that might be utilized for the assembly of large space structures in orbit. Since then, a new field of research has developed for the systematic scientific study of materials process in low gravity. Low gravity (0.01 to 0.0001 times normal Earth gravity) has been obtained utilizing parabolic aircraft flight, drop facilities,

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and sounding rockets. Microgravity conditions, for extended periods, can be provided by access to near Earth orbit. The emphasis over the last two decades has been on fundamental scientific data that can only be obtained in microgravity, and applying this new knowledge to improving industrially important materials processes on Earth.

Current proposals for developing an extended human presence, beyond space stations on the Moon and Mars, increasingly consider the processing of non-terrestrial materials essential for keeping the Earth launch burden reasonable. Materials processing in low gravity, however, can differ quite significantly from the same processes on Earth. The absence of buoyancy driven flow, for example, changes the solidification processes that are fundamental to most manufactured goods. In space, solidification can yield lower defects and more homogeneous crystals which could yield better semiconductors for computer chips, or could increase the grain size and change phase composition of metal alloys which could yield poorer mechanical properties. Thus, just as terrestrial materials science has been essential for technological advance on Earth, it is expected that materials science in low gravity will enable cheaper, more robust, methods for extended human presence beyond Earth orbit. In this paper, the use of *in situ* resources to produce metal alloys for use on Moon or Mars bases is discussed. The particular focus is candidate metallurgical extractive processes, new hierarchy of materials specific properties, and the effects of reduced gravity on microstructure and materials properties.

Hierarchy of materials

Utilization of materials for specific applications is based on their mechanical properties. An example of such a hierarchy is given in Figure 1, where tensile strength is used as the main criterion. Based on this criterion the best material is low-alloy steel and the poorest is magnesium. Other criteria such as yield strength, elasticity modulus, elongation or combinations of these can be also selected. This hierarchy is acceptable when the weight of the part is not an issue. However, if weight becomes an issue as in aerospace applications, or even in today automotive applications, other criteria that take density or weight into account may be used (Table 1). Such a criterion may be the ratio tensile strength/density (specific strength), or maximum load/unit weight. The later is preferable for this analysis since it includes the role of gravitational acceleration. Furthermore, it is nondimensional. The order will be changed, with titanium becoming the best and gray iron the least desirable material (Figure 2). Magnesium becomes more competitive.

Table 1. Quality criteria used to establish an hierarchy of materials

Quality Criterion	Symbol	Units
tensile strength	*TS*	MPa
tensile strength/density	*TS*/*r*	m^2/s^2
load/unit weight [#]	*TS*/(·g)	-
cost/load/unit weight	$/(*TS*/ ·g)	$

[#] for unit length

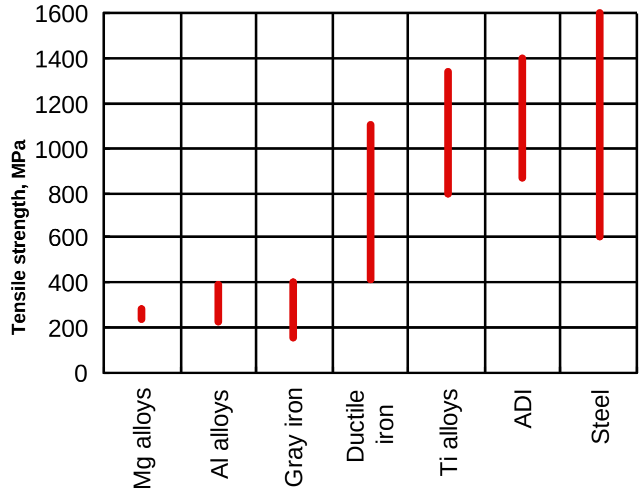

Figure 1. Hierarchy of materials based on tensile strength.

The planets of interest for this discussion have significantly different gravitational accelerations than the Earth (Moon -0.125 *g*, Mars -0.369 *g*). Because of the change in the *g* level, the numbers will change again. However, changes in *g* alone will not reorder the hierarchy but will move values proportional with gravitational acceleration.

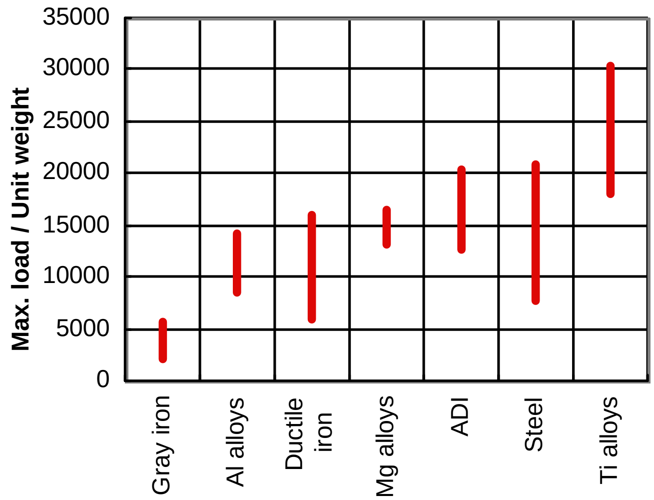

Figure 2. Hierarchy of materials based on maximum load / unit weight.

Further significant change in hierarchy will be brought about if cost is included in the criterion used. As illustrated in Figure 3, where the cost was assumed to be the processing cost on earth, titanium becomes the least desirable. Since weight is included in the evaluation criterion, the gravity level will affect the numbers. While, as indicated before, the hierarchy will not be altered, the difference between the various materials will change as a function of gravity level, as shown in Figure 4. As gravitational acceleration decreases, material criteria decreases. What this means is that on the moon, the decision to select one material over another may be based mostly on the availability of the material, since the differences on the cost / load / unit weight criterion are minimal. However, processing costs may be widely different than those on earth, an issue that will be addressed in the next section.

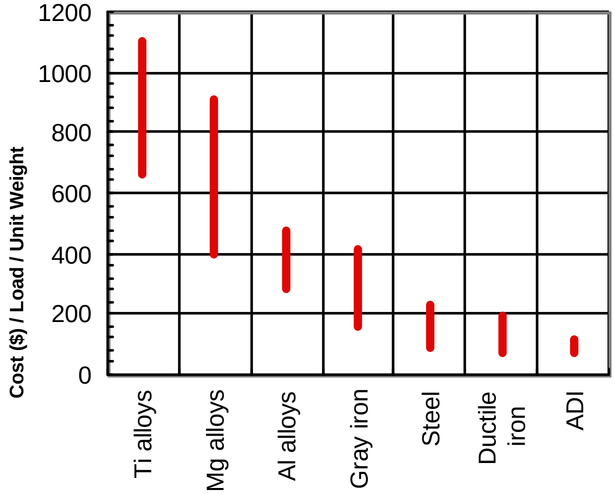

Figure 3. Hierarchy of materials based on cost / load / unit weight.

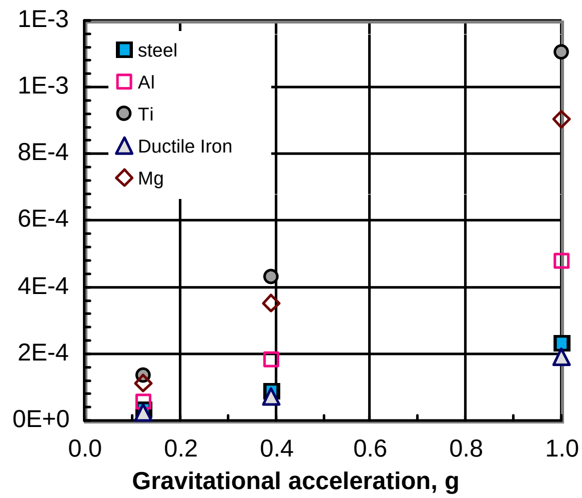

Figure 4. Influence of gravity level on the cost / load / unit weight criterion.

<u>Materials availability and extraction</u>

Relatively tiny amounts of native iron, either formed under unusual conditions (McGannon 1971) or found in some meteorites (Buchwald 1975) do exist. Iron, however, prefers to be combined with oxygen and its ores, e.g., hematite (Fe_2O_3) and magnetite (Fe_3O_4), are well represented, although not uniformly distributed, in the Earth's crust. While the high temperatures required to reduce these ores precluded early man from producing pure metal, a spongy mass consisting of iron and slag was formed that could be hot-worked to useful shapes. The blast furnace eventually evolved in which the combination of ore, flux (limestone), coke (distilled coal) and air produced a high carbon “pig” iron. Today, in view of economy and properties, iron and its alloys are by far the most utilized metals.

The intent of this briefest introduction to iron production is to convey a sense of its long history and the associated trials and tribulations encountered and overcome in developing the science and technology to what it is today. Similar convoluted developments characterize production of other metals of interest including aluminum, magnesium, and titanium.

Space expeditions have found metal bearing rocks and soils, i.e., resources, on two of our nearest planetary neighbors, the Moon and Mars. A summary of typical soil analysis for the three celestial bodies of interest is given in Table 2.

According to the present surveys, the Moon has soils particularly rich in Al in its Highland regions, and in Ti in its Mare regions. Both the Moon and Mars have significantly higher levels of Fe than Earth. Thus, if the composition of the soil is any indication of the availability of these metals for extractive processes, and based on the analysis of the hierarchy of materials presented above, it is anticipated that iron and titanium will play a major role in the material competition to build the structures needed for extension of human civilization to the Moon and Mars.

Body	O	Mg	Al	Si	S	Ti	Mn	Fe
Earth	47	2.3	8	27	0.04	0.5	0.1	5.1
Mars	42-45	2-5.5	4.2-6.6	20-26	0.9-2.5	0.4-0.7	0.4-0.7	10-15
Moon	40-45	4.9-6.8	5.8-14	19-22	0.06-0.1	0.3-5.6	0.05-0.2	4-15

Table 2. Typical soil analysis (wt.%) of celestial bodies of interest*
*****(O’Leary 1982; APXS 1997)

As the Moon lacks an atmosphere, its surface is subjected to exposure by hydrogen carried in the solar wind. This hydrogen reduces FeO in the soil to fine iron particles (O’Leary 1982) and, should sufficient quantities exist, would be an ideal source for raw material. Iron containing ilmenite ($FeTiO_3$) is also found in the lunar soil (Criswell 1982, O’Leary 1982) but must be reduced, albeit by “non-traditional” methods. In short, Fe_2O_3 is a reaction product when ilmenite is subjected to molten sodium hydroxide(O’Leary 1982), and iron can eventually be obtained through a carbochlorination process (APXS 1997). Silicon will reduce FeO to iron at 1300 °C. Hydrofluoric acid can be used as a leaching agent after which iron can be recovered by electrowinning (O’Leary 1982). It has also been suggested that the sun’s energy could be focused to reduce Moon ores through vaporization (O’Leary 1982).

The existence of iron ore on the surface of Mars has been recently confirmed. Results from the alpha proton x-ray spectrometer within the Pathfinder rover determined the soil to consist of 17.5 wt.% FeO and a given rock (“Barnacle Bill”) contained 12.7 wt.%. The ready presence of this ore already provides a processing advantage over having to reduce ilmenite in the moon's stark environment. Furthermore, the carbon dioxide rich atmosphere of Mars provides a very important resource. In combination with hydrogen (which, if not tied up in the polar cap or permafrost as water, may have to be imported) several well known and characterized reactions can be implemented (APXS 1997). Now, using well established technologies, carbon monoxide, water, and methane (CH_4) can be produced and collected. CO will reduce (solid) FeO at a temperature below 800 °C (Figure 5). Thus, the atmosphere of Mars not only provides a basis for life support and fuel production but could well facilitate iron production.

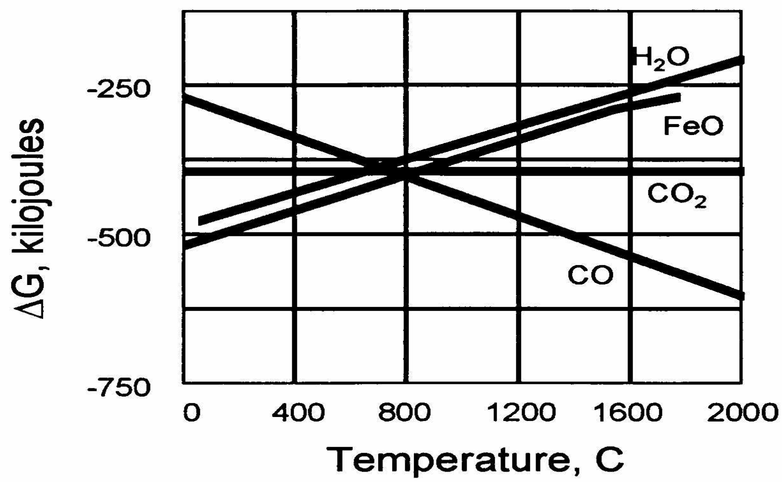

Figure 5. Simplified Ellingham Diagram

Obviously, there will be considerable technical and financial challenges before iron, steel, titanium, etc. components are produced on extraterrestrial bodies. However, this goal appears to be entirely attainable.

<u>Solidification processing</u>

The main characteristics of the lunar and Martian environment that will impact on processing techniques are lower atmospheric pressure and lower gravity. It is difficult to anticipate at this time how the price structure of the materials of interest will be altered during processing on the Moon or Mars. However, it is clear that significant changes are expected in the behavior of liquid metals during processing. This, in turn, will affect the price. Some of the issues that must be addressed include melting and casting techniques.

<u>Melting techniques</u>

Melting of metals on planet Earth ranges from cheap air melting of non-reactive alloys (most ferrous and non-ferrous alloys) to expensive vacuum melting of reactive alloys (titanium alloys, superalloys). On both the Moon and Mars the atmosphere is extremely poor in oxygen, and thus it is anticipated that the price of melting of reactive alloys will be much closer to that of non-reactive ones. This will change the relative spread of material (shown in Figure 4) to the benefit of titanium and magnesium.

Melt containment is another relevant issue for reactive metals since they tend to react with most ceramics used in classic processes. Recent progress in magnetic containment melting (MCM) will find a much favorable environment on Moon and Mars. The reduced gravitational acceleration will impose significantly lower requirements on the size of the coils and the energy consumption. In particular a combination of cold-wall induction melting and MCM (Figure 6) may prove to be the method of choice for melting titanium and its intermetallics.

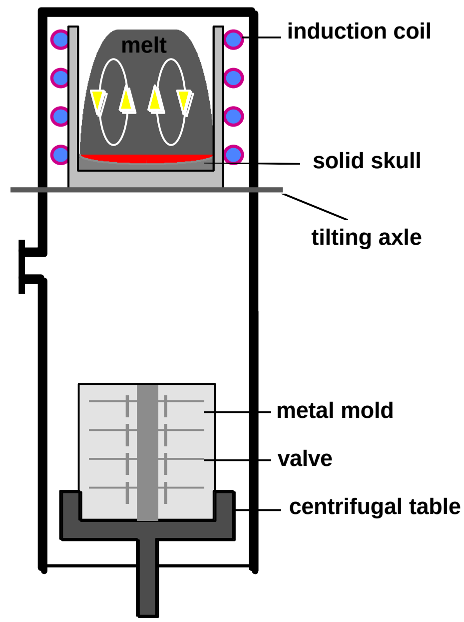

Figure 6. Cold-wall magnetic containment melting.

Casting techniques

Most earthly casting processes rely on gravity to help fill the mold, hence the name "gravity casting." Gravity also imposes conveniently the position of shrinkage cavities in the upper part of the casting. The absence of gravity or very low gravity levels (μg) are known to create problems for scientist experimenting with solidification in space. Indeed, obtaining sound samples is invariably a problem in shuttle experiments. Some pressurization during solidification may be required to improve casting soundness in the absence of gravity. Gravity casting has a major disadvantage: metal flow is in the turbulent regime. This results in gas and solid inclusions being incorporated in the casting, which alters the quality of the cast material.

To produce premium castings counter-gravity casting is used. In this process, the metal is fed into the mold from the bottom by applying pressure on the liquid metal (Figure 7). The free vacuum on the Moon and Mars will make counter-gravity casting a very competitive process.

Material properties

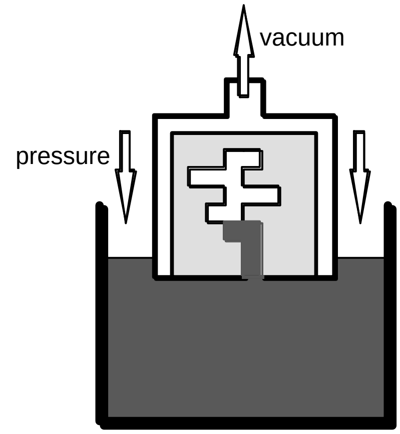

Figure 7. Principle of counter-gravity casting.

Gravitational acceleration strongly influences solidification processes through Stokes flow, hydrostatic pressure, and buoyancy-driven thermal and solutal convection. Microstructural development and therefore material properties, presently being documented through ongoing research in microgravity science and applications, needs to be understood and scaled to the reduced gravity environments. Comparison of solidification data in microgravity on orbital platforms, 10^{-4} *g* on sub-orbital sounding rocket flights, and 10^{-2} *g* on parabolic aircraft trajectories with solidification data taken on Earth have documented gravity dependence in microstructure (Curreri 1988). Convection has been shown to strongly influence solute redistribution. Continual buoyancy-driven mixing of the liquid ahead of the solidification interface (for partition coefficient not equal to 1) in one-gravity causes alloy macrosegregation. In low-*g* a steady state diffusion controlled boundary layer can form resulting in sample solute homogeneity. Eutectic alloy microstructures, for example cast iron, are strongly dependent upon the magnitude of gravity during solidification. Spacings of eutectic fibers, flakes, and lamella, nucleation of graphite grains, spacing of primary dendrites can be quite different from that obtained on the laboratory or foundry on earth when solidification occurs in low-*g*. Thus, handbook values for alloy mechanical and electrical properties compiled in 1-*g* cannot be relied upon for *in situ* resource processing on the Moon or Mars.

Conclusions

The Moon and Mars offer rich sources of ores that can be exploited to produce metals for electrical conductors and structural materials. The new hierarchy of materials in terms of specific properties must be considered. Processing methods of choice are influenced by the low pressure atmospheres and lower gravity present on these worlds. The influence of gravity on the microstructures created by solidifying under reduced gravity must be understood and applied before the engineering properties of these *in situ* produced materials can be accurately determined.

Acknowledgments

We wish to acknowledge the support of the NASA Microgravity Science and Applications program. One of the authors, (RNG), gratefully acknowledges the support of NASA Grant NCC8-66 and the Universities Space Research Association.

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<u>Key Words</u>

Moon
Mars
Casting
Extraterrestrial Resources